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Linking Climate Change information with Crop Growing Seasons in the Northwest Ethiopian Highlands

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Abstract: In Ethiopia, climate change risks are anticipated to have significant consequences for agriculture and food security. This study investigated the past (1981-2010) and the future (2041-2070) climate change trends and their influence on crop length of growing seasons in North-Western (NW) Ethiopian highlands. Climate data were obtained from National Meteorological Agency of Ethiopia and the most valid and high resolution CMIP5 rcp6 (Coupled models Intercomparison Project representative concentration path six) model data were extracted and applied for the analysis purpose. Standard statistical methods are then applied to compute soil water content as well as to evaluate climate variability and trends and their impact on crop Length of Growing Season (LGS). Maximum temperature (tasmax) and minimum temperature (tasmin) inter-annual variability anomalies show the region has experienced coolest years than hottest years during the past. However, in the future the coolest years will highly decrease by -1.2°C while the hottest years increase by +1.3°C. During the major rainfall season (JJAS), the area has received an adequate amount of rainfall in the past and is very likely to get similar rainfall in the future. Whereas the February to May (FMAM) season assists only for early planting and October to January (ONDJ) season for lengthen growing season of JJAS if properly utilized. Otherwise, the season will have the possibility to destroy crops before and during the harvesting time. The soil water content change in the future remains close to past condition, The length of growing seasons has less variable onset and cessation dates while the projected length of growing period (LGP) 174 to 177 days will be suitable for short, long cycle crops and double cropping that could benefit crop production yield of NW-Ethiopian highlands in the future.

Keywords: rainfall; temperature; potential evapotranspiration; soil water content; climate projection

1. Introduction

There is consensus that the impacts of climate change on agriculture will add significantly to the development challenges of ensuring food security and reducing poverty, particularly in Africa. Climate change plays a great role in agricultural production having a direct impact from the start of land preparation to the final harvest (Akinseye, 2013; Mesike and Esekhade, 2014, Alemayehu, 2016, 2017) In the recent half century, Ethiopia has been experiencing late onset and early cessation of seasonal rains and associated failure of the crop growing season (Wing, 2008 Alebachew and Woldeamlak, 2011). Hence, to optimally utilize the seasonal rainfall for agricultural production, additional knowledge and understanding is needed on how shifts in rainfall seasons may affect crop yields. This needs predictive information of the start and end of the growing season that also assists to take appropriate adaptation and coping measures.

Climate change has an impact on different growth and development processes of crops. For example, an increase in CO_2 will stimulate photosynthesis rates and sometimes result in higher yields

(Kimball, 1983 cited in Benedicta et al 2012). Changes in temperature and precipitation will affect crop photosynthesis, and plant development rates, as well as water and nutrient budgets in the field (Long, 1991). One of the most important processes that will be affected by climate change is photosynthesis. The direct effects of CO_2 enrichment on plants are that an increase in CO_2 concentrations increases the rate of photosynthesis and water-use efficiency (WUE). As CO_2 concentration increases, the transpiration intensity of plants reduces by partially closing the stomata, which leads to improved water use efficiency and thereby lowers the probability of the occurrence of water-stress. These physiological responses are known as the CO_2 -fertilization effect or the direct effect of increased CO_2.

The increase in temperature due to climate change has both positive and negative impacts on crop production. For example, in the middle and higher latitudes and at high elevations in the tropics, global warming will extend the length of the potential growing season, allowing earlier planting of crops in the spring, earlier maturation and harvesting. Increased CO_2 may allow for the possibility of completing two or more cropping cycles during the same season and allow crop producing areas to be expanded to higher latitudes and elevations, providing that soil fertility is maintained (Rosenzweig et al., 2004, Benedicta et al, 2012). In warmer, lower latitude regions, increased temperatures may increase the rate at which plants release CO_2 in the process of respiration, resulting in less-than-optimal conditions for net growth. High temperature reduces yield by accelerating physiological development (hastening maturation), not allowing the crop to progress slowly through the season to maximize time for the capture of resources and for assimilated partitioning to reproductive structures (David and Sharon, 2012). Therefore, under conditions that are physiologically 'too warm' for certain crops, yields may decrease.

An increase in average temperature can have several effects. First, it can lengthen the growing season in regions with a relatively cool spring and fall. It could also adversely affect crops in regions where summer heat already limits production. Soil evaporation rates may increase, and the chances of severe droughts may also rise (Rosenzweig and Tubiello 1997, Sombroek and Gommes, 1996). Warmer temperatures in high altitude areas may allow more insects to overwinter in these areas. Crop damage from plant diseases is likely to increase in temperate regions because many fungal and bacterial diseases have a greater potential to reach severe levels when temperatures are warmer or when precipitation increases (Rosenzweig and Hillel 1995). Changes in rainfall can affect soil erosion rates and soil moisture, both of which are important for growth and yields. In the case of NW-Ethiopian highland the impact of climate change is likely to have both positive and negative impact as the area has different topography with high, middle, and low altitude elevations.

Moreover, improved forecasts of seasonal precipitation with adequate spatial resolution could potentially increase agricultural production and reduce production risks (Robertson et al., 2007). Therefore, predictions of local determinants of climate change, climate variability and growing season are crucial for livelihoods dependent on rain-fed agriculture. Hence, this study uses fine resolution climate change models to simulate and project climatic conditions and associated growing seasons in the NW-Ethiopian highlands.

According to the World Bank (2004) categorization the NW-Ethiopian highlands majority areas as potential zone with substantially higher rainfall and more availability of arable land in which the average crop yield is double of the whole country. Even though NW-Ethiopian highlands are the crop production and livestock potential areas, the rainfall is erratic in terms of both spatial and temporal distribution, with dry spells that significantly reduce crop yields and sometimes lead to total crop failure resulted the highlands to face recurrent drought (World Bank, 2004). The Ethiopian highlands, the major contributor of crop production for the country, were affected by inter-annual and seasonal variability of rainfall causing fluctuations of cereals production in the region (Woldeamlak, 2009). Hence research on climate change impact on crop production and agricultural water management is timely and important to enhance food security in the country. Although some studies have been made to identify the spatial and temporal climate change of the past and the future, these have not specifically been tied to the growing season at local level (Thornton, 2009; Gebrehiwot, 2013; Asrat, 2018 and Alemayehu, 2016, 2017). Moreover, the impact analysis of climate change on

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soil water content and the onset and cessation date and length of growing period derived from soil water content mostly provides reliable result than other methods used to determine crop growing seasons. Hence, this research analysed climate change and its impact on the length of the growing season (based on soil water content) in the Ethiopian highlands. In which the research result can, then, be used to design suitable adaptation and mitigation strategies as well as coping mechanisms.

Thus, in this study, we addressed the past (1981-2010) and future (2041-2070) CMIP5 rcp6 model projections comparative observations of trends and changes in specific climatic parameters (rainfall, maximum and minimum temperatures, PET, and soil water content) and their impact on length of crop growing seasons in the NW-Ethiopian highlands.

2. Materials and method

2.1. Study area

The NW-Ethiopia highlands are situated in the north-western part of Ethiopia, located within 8– 14^{O}N and 35–39^{O}E extracted from an objective cluster analysis of rainfall data as shown in Figure 1.

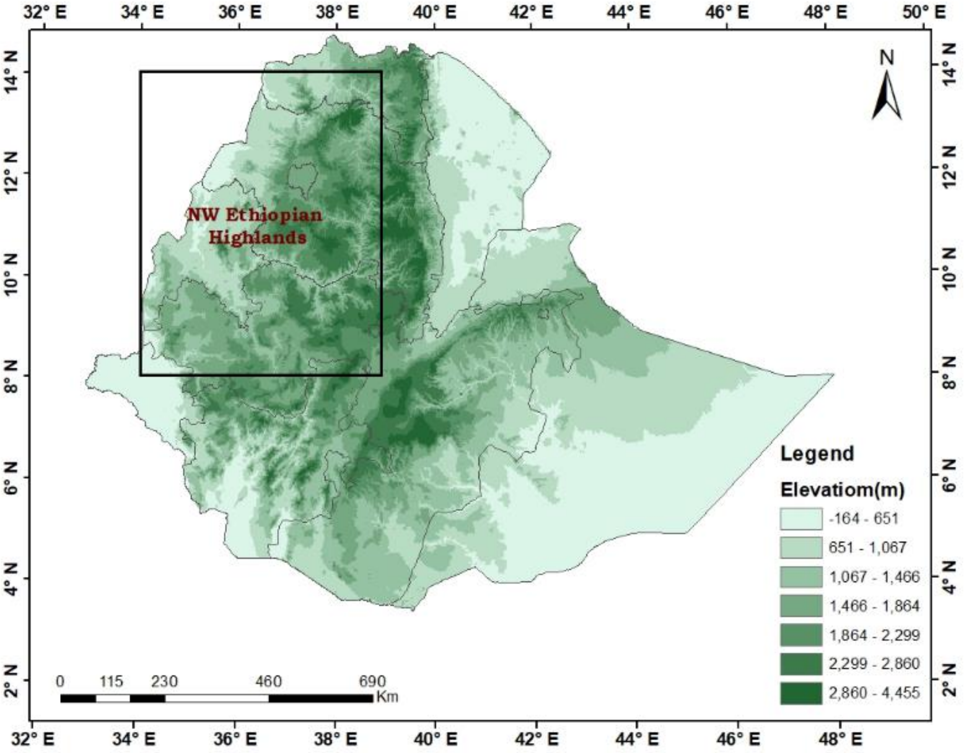

Figure 1. Map of NW-Ethiopia highlands using International Centre for Tropical Agriculture (CIAT) map. Source: (Jarvis et al., 200).

Agriculture of the study area

Agriculture has been practiced for centuries in Ethiopia. The overall farming system is strongly oriented towards grain production as source of livelihood and way of life. Ethiopian peasant agriculture has polyculture (the traditional rotation of crops and livestock) character. This kind of agriculture continued for centuries and remains better for both the land and the people as it met the complete livelihood and nutritional needs and security of the community. Accordingly, though the sector has remained subsistent, a peasant can produce everything required for himself and his family. A peasant could produce a variety of crops. The proximity of areas of different altitude seems to have contributed for the multiplicity of crops. Farmers produced mainly food crops except few cash crops that would serve in the local market or barter system. Nevertheless, Ethiopia has seen droughts in the recent half century (Alebachew and Woldeamlak, 2011) mostly caused by late onset and early cessation of seasonal rains and associated failure of the crop growing season as the agricultural practice of most farmers in the country is dependent on rain-fed agriculture. Hence, to optimally utilize the seasonal rainfall for agricultural production, additional knowledge is needed on how shifts in rainfall seasons may affect crop yields. On the other hand, the Ethiopian highlands soil type is dominantly Vertisols account for 12.7 million hectares in Ethiopia of which 7.6 minion hectares. Waterlogging of Vertisols is more severe in the Ethiopian highlands where rainfall is higher and evaporative demands are lower. The technical efficiency of the traditionally applied surface drainage techniques is not sufficient to allow full use of the potentials of these soils.

2.2. Data sets and research design

The data sources used for analysis were from stations gauge data, gridded observation (reanalysis) data and CMIP5 rcp6 (representative concentration path 6) model simulation datasets extracted from the KNMI-Climate Explorer website (climexp.knmi.nl). Each of the variables: rainfall, sensible heat flux (shf) and temperature were area-averaged for NW-Ethiopian highlands, for temporal and spatial analysis. The procedures and the methods designed to compute soil water content incorporating RO (Runoff) (not in Thornwaite soil water balance method) and Thornwaite and Mather soil moisture retention table have significant role to study soil moisture in the NW-Ethiopian highlands (Thornwaite and Mather). The soil moisture changes obtained from the computed soil water content were applied to determine onset date, cessation date and LGP of the study area.

2.3. Determining the best reference for validation

Before evaluating the models, the optimal reference was determined for temperature, rainfall and (Potential Evapo-Transpiration) PET variables. For tasmax the Climate Research Unit Time Series (CRU TS v3.22) interpolated observations were compared with 35 stations averaged over the study area from 1981-2000. The correlation is r=0.95 with a minor cold bias of -0.09^{O}C. This implies CRU TS v3.22 is a reliable data source of temperature for the validation and evaluation of CMIP5 rcp6 models' data sources for temperature and to select the most appropriate model. Comparing Global Precipitation Climatology Center version 6 (GPCC v6) rainfall with the area-average of 35 station observations rainfall 1981-2000, a correlation of r=0.99 is found with minimal dry bias of GPCC -0.6 mm/day using the scatter plot. Hence GPCC v6 at 50 km resolution correctly handles Ethiopia's orographic effect on rainfall and can be used for the validation and evaluations of CMIP5 rcp6 models' data source for precipitation and choose the most appropriate model. The climate model selected for rainfall simulation then again applied to derive soil water content and length of growing season in the NW-Ethiopian highlands in the past (1981-2010) and in the future (2041-2070). Inline to this GPCC rainfall products have shown good agreement with reference gauge data in research conducted by Fuchs et al. (2007) and Tufa et al. (2008) on the Ethiopian highlands.

PET calculated using 18 stations from Muluneh (2008) and Banchiamlak (2009) in the NW-Ethiopia highlands and Climate Research Unit - Potential Evapo-Transpiration (CRU-PET) used as references for comparison with other datasets and proxies, such as maximum temperature and surface heat flux. The relation between station PET and CRU maximum temperature was significant but it is known that temperature lags solar radiation (Ojo, 1977) so screened out. In comparison with ECMWF reanalysis adjusted sensible heat flux (adjshf), a regression of R^2=0.95 indicates a robust relation. Weaker correlations were determined between station PET and Modern Era Retrospective-Analysis (MERRA) reanalysis adjusted sensible heat flux. Thus, European Centre for Medium-Range Weather Forecasts (ECMWF) adjshf served as the validation reference for CMIP5 rcp6 sensible heat flux, after adjustment to match ECMWF adjshf.

2.4. Models validation and evaluation

The evaluation of monthly gridded observation, reanalysis gridded data from GPCC v6 (for rainfall) and CRU TS v3.22 (tasmax) and ERA-Interim (adjshf) compared with station observation data and revealed (r>0.90) used for the validation of CMIP5 rcp6 model's area-averaged over the NW-Ethiopia highlands. Stepwise criteria gave a basis for comparison, and the models that achieved most of the criteria were CCSM4 (for tasmax) and HadGEM2-ES (for precipitation and PET/adjshf). Thus, these two CMIP5 models were used for projection of climate change and to compute soil water content and determine the length of the growing season of the past and the future in the study area. In line with the above stepwise criteria to evaluate and justify CMIP5 rcp6 model's simulations against GPCC V6 (Rainfall), CRU TS3.22 (tasmax) gridded observations and ERA-interim (shf) reanalysis gridded observation have been proposed in the context of the Ethiopian highland's climate by Tufa et al. (2008) and Jury (2015). The detail how the reference models are selected for precipitation, temperature and sensible heat flux is presented in Tables 1–3 respectively.

Table 1. NW-Ethiopian highlands CMIP5 rcp6 model's rainfall stepwise evaluation taking GPCC v6 as reference from 1981-2010. CMIP5 rcp6 rainfall models validation taking GPCC V6 as reference from 1981-2010.

No	Model	GPCC v6(r)	JJAS- diff. (GPCC v6 Vs rcp6)	Season peak- JA/day)	Annual pattern fitness	Remark
1	bcc-csm1-1	0.65	-3.2	3.8	poor	Screened out
2	bcc-csm1-1-m	0.90	-1.4	6.3	poor	Screened out
3	CCSM4	0.76	-2.0	4.3	poor	Screened out
4	CESM1-CAM5	0.75	-0.9	5.7	poor	Screened out
5	CSIRO-Mk3-6-0	0.91	-1.1	8.8	moderate	Screened out
6	FIO-ESM	0.80	-2.1	4.6	poor	Screened out
7	GFDL-CM3	0.87	-1.5	6.2	poor	Screened out
8	GFDL-ESM2G	0.86	-0.3	6.7	moderate	Screened out
9	GFDL-ESM2M	0.87	-0.5	6.4	moderate	Screened out
10	GISS-E2-H_p1	0.96	-5.3	3.2	poor	Screened out
11	GISS-E2-H_p2	0.96	-5.5	2.8	poor	Screened out
12	GISS-E2-H_p3	0.96	-4.7	4.0	poor	Screened out
13	GISS-E2-R_p1	0.97	-5.6	2.5	poor	Screened out
14	GISS-E2-R_p2	0.97	-5.7	2.6	poor	Screened out
15	GISS-E2-R_p3	0.96	-5.3	2.7	poor	Screened out
16	HadGEM2-AO	0.96	-0.4	8.1	high	2nd selected
17	HadGEM2-ES	0.97	-0.5	8.0	high	1st selected
18	IPSL-CM5A-LR	0.89	-2.7	6.3	poor	Screened out
19	IPSL-CM5A-MR	0.90	-3.3	5.3	poor	Screened out
20	MIROC5	0.98	11.5	21.1	poor	Screened out
21	MIROC-ESM	0.86	-0.5	7.3	high	Screened out
22	MIROC-ESM-CHEM	0.88	-0.5	7.4	high	Screened out
23	MRI-CGCM3	0.93	-2.5	6.0	moderate	Screened out
24	NorESM1-M	0.66	-2.7	3.4	poor	Screened out
25	NorESM1-ME	0.62	-2.3	3.3	poor	Screened out

Table 2. CMIP5 rcp6 models' maximum temperature (tasmax) stepwise evaluation taking CRU TS3.22 as reference from 1981-2010.

CMIP5 rcp6 tasmax models stepwise evaluation using CRUTS 3.22 as reference from 1981-2010					
No	Model type	CRUTS 3.22 tasmax (r)	Seasonal peak /MAM diff.(CRUTS 3.22 Vs rcp6)	Annual pattern fitness	Remark
1	bcc-csm1-1	0.90	2.0	Poor	Screened out
2	bcc-csm1-1-m	0.35	-1.4	Poor	Screened out
3	CCSM4	0.98	-0.5	Highly	1st selected
4	CESM1-CAM5	0.90	-2.3	Poor	Screened out
5	CSIRO-Mk3-6-0	0.43	-1.8	Poor	Screened out
6	FIO-ESM	0.81	1.6	Poor	Screened out
7	GFDL-CM3	0.90	3.6	Poor	Screened out
8	GFDL-ESM2G	0.91	-1.0	Moderately	Screened out
9	GFDL-ESM2M	0.92	-0.7	Moderately	4th selected

10	GISS-E2-H_p1	0.94	4.0	Poor	Screened out
11	GISS-E2-H_p2	0.90	4.0	Poor	Screened out
12	GISS-E2-H_p3	0.95	3.9	Poor	Screened out
13	GISS-E2-R_p1	0.97	4.7	Poor	Screened out
14	GISS-E2-R_p2	0.93	4.8	Poor	Screened out
15	GISS-E2-R_p3	0.95	4.8	Poor	Screened out
16	HadGEM2-AO	0.91	0.2	Moderately	3rd selected
17	IPSL-CM5A-LR	0.20	-1.1	Poor	Screened out
18	IPSL-CM5A-MR	0.22	1.1	Poor	Screened out
19	MIROC5	0.93	-3.3	Poor	Screened out
20	MIROC-ESM	0.93	3.2	Poor	Screened out
21	MIROC-ESM-CHEM	0.94	2.8	Poor	Screened out
22	MRI-CGCM3	0.85	0.9	Poor	Screened out
23	NorESM1-M	0.94	0.3	Highly	2nd selected

Table 3. Stepwise evaluation result comparing CMIP5 rcp6 models sensible heat flux (SHF) with adjshf ECMWF-ERA-int. to simulate adjshf for NW-Ethiopia highlands based on years 1981-2010.

No	CMIP5 rcp6 models	ERA Vs rcp6 PET/adjshf (r)	Seasonal diff. FMA (ERA Vs rcp6)	Annual cycle fitness	Remark
1	bcc-csm1-1-m	0.79	0.46	moderate	Filtered out
2	bcc-csm1-1	0.73	0.72	poor	Filtered out
3	CCSM4	0.96	0.63	high	2nd selected
4	CESM1-CAM5	0.78	0.06	moderate	Filtered out
5	CSIRO-Mk3-6-0	0.79	1.04	poor	Filtered out
6	FIO-ESM	0.95	0.81	high	4th selected
7	GFDL-CM3	0.92	1.26	poor	Filtered out
8	GFDL-ESM2G	0.9	0.92	Moderate	Filtered out
9	GFDL-ESM2M	0.92	0.88	Moderate	Filtered out
10	GISS-E2-H_p1	0.95	1.48	poor	Filtered out
11	GISS-E2-H_p2	0.96	1.32	poor	Filtered out
12	GISS-E2-H_p3	0.97	1.21	poor	Filtered out
13	GISS-E2-R_p1	0.95	1.29	poor	Filtered out
14	GISS-E2-R_p2	0.97	1.11	poor	Filtered out
15	GISS-E2-R_p3	0.97	1.04	moderate	Filtered out
16	HadGEM2-AO	0.93	0.34	high	Filtered out
17	HadGEM2-ES	0.96	0.24	Very high	1st selected
18	IPSL-CM5A-LR	0.87	1.52	poor	Filtered out
19	IPSL-CM5A-MR	0.74	1.34	poor	Filtered out
20	MIROC5	0.95	-0.95	Moderate	Filtered out
21	MIROC-ESM	0.87	0.11	Moderate	Filtered out
22	MIROC-ESM-CHEM	0.85	0.05	Moderate	Filtered out
23	MRI-CGCM3	0.8	0.31	Moderate	Filtered out
24	NorESM1-M	0.95	0.58	high	3rd selected
25	NorESM1-ME	0.91	0.44	high	Filtered out

Table 4. Computation of monthly Acc. Pot. WL, soil water storage, soil water storage change and actual evapotranspiration (mm/month).

Time period	Parameter	Jan	Feb	Mar	April	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
Past (1981-2010)	Rainfall	7	11	29	89	147	197	217	231	171	74	23	14
	RO	2.2	3.5	9.3	28.5	47.0	63.0	69.4	73.9	54.7	23.7	7.4	4.5
	PET/Es	110	121	126	123	112	92	81	81	86	93	99	103
	P-Es-RO	-105	-114	-106	-62	-12	42	67	76	30	-43	-83	-93
	ACC.P.WL	-325	-439	-545	-607	-619					-43	-126	-220
	ST	38	22	13	9	8	50	117	193	200	161	105	66

	ΔST	-28	-16	-9	-4	-1	42	67	76	7	-39	-56	-39
	AE (P+ΔST)	35	27	38	93	112	92	81	81	86	93	79	53
Future (2041-2070)	Precipitation	8	9	26	92	161	211	216	227	188	86	26	15
	RO	2.6	2.9	8.3	29.4	51.5	67.5	69.1	72.6	60.2	27.5	8.3	4.8
	PET/Es	123	140	152	139	111	94	84	82	84	88	97	108
	P-Es-RO	-118	-134	-134	-76	-2	49	63	72	44	-30	-79	-98
	ACC.P.WL	-325	-459	-593	-669	-671					-30	-109	-207
	ST	39	20	10	7	7	56	119	192	200	172	115	70
	ΔST	-31	-19	-10	-3	0	49	63	72	8	-28	-57	-45
	AE (P+ΔST)	39	28	36	95	111	94	84	82	84	88	83	60

[1] Ro=Runoff, PET=Potential Evapotranspiration, Es =, Actual Evapotranspiration, ACC.P.WL=Accumualted potential watrloss, ST= soil moisture storage ΔST=soil moisture change.

2.5. Climate change analysis

Of the many ways to understand climate change, the difference of future minus past is often used. This is easy to interpret but suffers from uncertainties of natural climate variability, depending on the variable and periods used. The climatological reference period of 30 years (WMO, 2014) used here is 1981-2010. This is a compromise between the longer period needed for precipitation and a shorter one that is sufficient for temperature. Another point is that trends in the most recent 30-year period are more relevant to the next 30-year period, especially given the known acceleration of greenhouse warming. Linear trends are used to evaluate the signal-to-noise ratio instead of differences between two periods. The trend can be described as proportional to CO_2 concentration or the global mean temperature. Although CO2 trends are accelerating (Figure 2) the temporal response of climate may be assumed to be linear over the period of study here. This removes ambiguities arising from 2nd order responses.

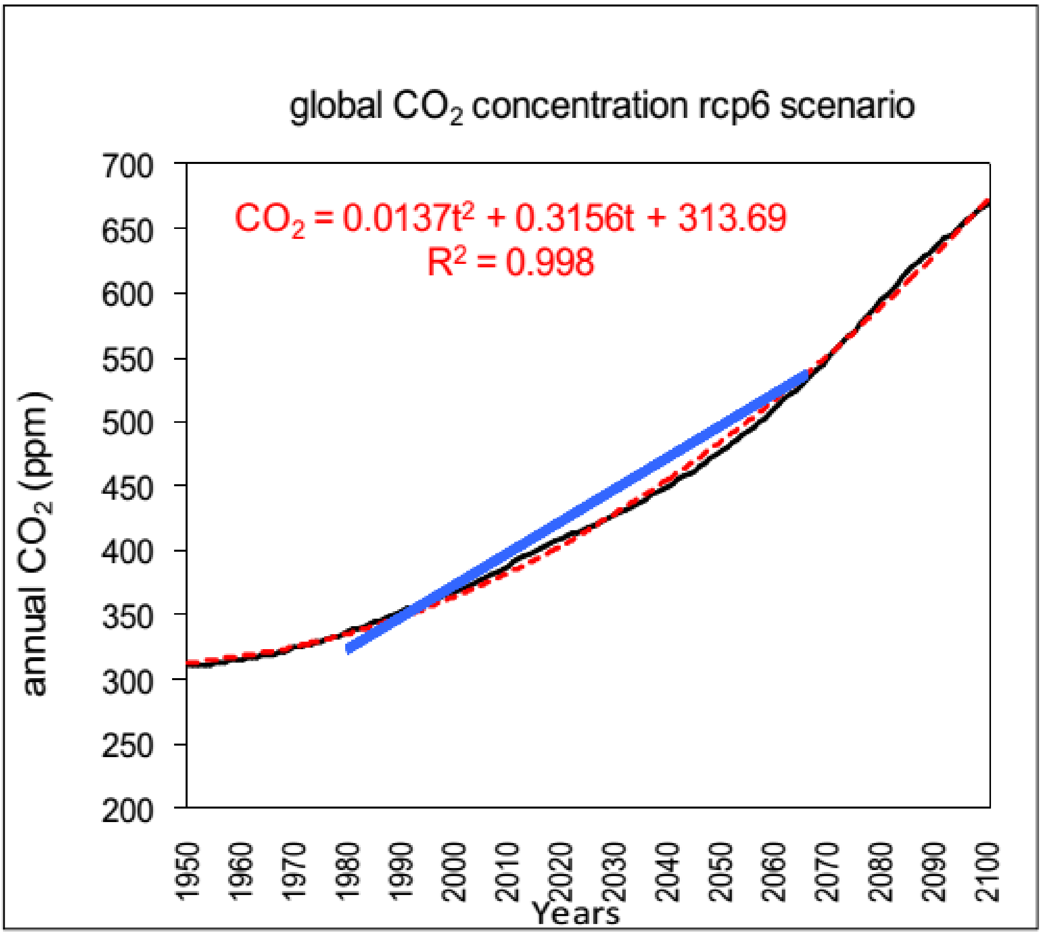

Figure 2. CMIP5 rcp6 scenario CO2 concentrations from 1950-2100, Source: Extracted from KNMI climate explorer web page.

Trends in rainfall and temperature can indicate 'drift' due to climate change (whether natural or anthropogenic). Detecting trends in the data may be useful in decision making at the policy level in agriculture and food security. A linear equation fitted by regression was used for trend analysis of temperature, rainfall, PET, and anomalies. Instat +v3.36 software (Stern et al., 2006) t-test was applied to check whether the changes are statistically significant or not. Bias is evaluated by comparison of the simulated or projected annual cycle against reference data for all the above variables. Negative bias is where the model minus reference is (< 0), so for rainfall that would be dry bias and for temperature a cold bias. Measures of association are statistical measures that demonstrate the strength or degree of relationship between two or more variables, thus the method employed using the Royal Netherlands Meteorological Institute-Climate Explorer (KNMI CE) climexp.knmi.nl. webpage and EXCEL 2007 and Instat +v3.36 software used to determine correlation coefficient and coefficient of determination by pairwise and stepwise multiple linear regression, both spatially and temporally. The 95% significance level is typically used as the threshold for validity.

2.6. Potential Evapotranspiration

From the different methods used to calculate PET the FAO Penman-Monteith method is recommended by FAO as the standard method (FAO, 1998). Nevertheless, in developing countries like Ethiopia it is not easy to get the climate parameters used to calculate PET. For this reason, a method used to surrogate PET by comparing other climate variables anticipated to replace PET comparison of estimate methods were applied. Thus, PET calculated from station observations by Muluneh (2008) and Banchiamlak (2009) in the NW-Ethiopia highlands and estimate of PET from the CRU data source were used as a reference to compare with CRU (tasmax), ECMWF and MERRA reanalysis sensible heat flux (shf), latent heat flux (lhf) and shf+lhf. Then, the comparison result, which was in a good agreement with PET station observation and CRU-PET estimate, was used to surrogate PET and further used to justify CMIP5 rcp6 models' data for the evaluation and analysis purpose.

2.7. Soil water content proxy

The spatial distribution and temporal variation of soil water content in the top metre of the earth's surface is important for numerous environmental studies. Soil water content can be determined from: (i) point measurements; (ii) soil water content models; and (iii) remote sensing. For the purpose of this study soil water content calculated from CMIP5 rcp6 models' data were applied to estimate soil water balance/soil water content change of the past and the future. Then using precipitation and surrogate of PET from CMIP5 rcp6 models the estimate of soil water balance (P-Es-RO) both in the past and in the future were calculated and used for the analysis of soil water balance in the region.

2.8. Growing season analysis

The LGP methodology is informed by Henricksen and Durkin (1987), Belay (2001), Masresha (2003) and Araya (2010); cf: section 2.17.1. The onset of the growing season requires build-up of soil water content depending on soil and crop type. When soil water change first becomes positive ($\Delta ST > 0$) the season is said to commence with germination. Similarly, the cessation time was estimated when the soil water content change becomes zero/negative ($\Delta ST \leq 0$). This methodology is carried over from past simulation to future projection. Although Ethiopia is a tropical country the highlands experience minimum temperatures below $9^{O}C$, which is a threshold that crops can no longer extract the available soil water (Henricksen and Durkin, 1987; FAO, 1996a; Thornton et al., 2006).

After identifying the CMIP5 model closest to observation, the growing season length in the study area was estimated using a proxy of water available for storage (P-Es-RO) where (P) and (Es), with (P) from section 4.2.1 and Es from section 4.2.2 and RO calculated from (P) and runoff coefficient (Cor) equation (9.1) taking Cro in between (0.15-0.32) which is an estimate of heavy soil, steep with slope ranging (2% to 7%) according McBean et al. (1995) for the detail. In which the computation takes place till only the last month of the wet season, water available for storage is equal to or greater than the water-holding capacity of the soil. The length of growing season was estimated from the CMIP5 rcp6.0 projection of soil water change (ΔST) obtained by the calculation of (P-Es-RO) as outlined below, based on (Thornthwaite, 1948; McBean et al. 1995; Nata, 2006 and Thornthwaite and Mather, as cited by Tesfaye 2014). The first step was to determine the soil, vegetation and crop type, root depth and water holding capacity of the study area so that to obtain the corresponding values from soil moisture retention tables of (Thornthwaite and Mather, 1957). Based on the options available (in Thornthwaite and Mather) for water holding capacities with different combinations of soils and crops (vegetations) tables, as the major crops of NW-Ethiopian highlands are corn and cereal grains. Hence the appropriate classification of the area is the moderately deep-rooted crops category with soil type: silt loam, water holding capacity 200 mm/m, root zone 100cm and applicable soil moisture retention table 200mm were used to estimate soil water content in this study.

Accumulated potential water loss is the potential deficiency of soil moisture associated with moisture contents below the water-holding capacity of a soil. Thus, for each soil moisture content there is an associated accumulated potential water loss. Accumulated potential water loss is 1) increased during dry seasons because of an insufficient supply of water to meet the demands of PET, 2) reduced during wet seasons due to the recharge of soil moisture, and 3) equals zero when soil moisture storage equals the water-holding capacity of the soil. The next step was to compute the accumulated potential water loss (Acc. Pot. WL). This accumulation starts from an estimated value of the potential water deficiency of the first month after the rainy season when (P-Es-RO) becomes negative (from Thornthwaite and Mather, 1957). Then progressively adding (P-Es-RO) with negative values for the remaining months can be obtained using:

$$\textbf{Equation 1} = Acc.Pot.WL_{i+1} = Acc.Pot.WL_{i+1} + (P - Es - Ro)_{i+1}$$

Where i is the current month and i+1 the next month from the current month.

If the soil moisture exceeds the water-holding capacity, the soil moisture is set equal to the water-holding capacity:

$$\textbf{\textit{Equation 2}} =$$

$$S_{m(j)} = \begin{cases} S_{m(j-1)} + (P - Es - Ro)_{(j)} \; for \; S_{m(j-1)} + (P - Es - Ro)_{(j)} < W_{WHC} \\ W_{WHC} \qquad\qquad\qquad\qquad for \;\; S_{m(j-1)} + (P - Es - Ro)_{(j)} W \geq_{WHC} \end{cases}$$

Where $S_{m(j)}$ is the soil moisture storage (in millimeter) for the *j*-th month w_{WHC} is the water-holding capacity of the soil.

The moisture retained in the soil is determined by converting each value of accumulated potential water loss into soil water content storage (ST) with the help of soil moisture retention table. The change in the soil moisture storage is the difference between the current and previous month's soil moisture storage, starting from December of each year and moving into the next growing season. In which, the change in soil moisture is positive if the soil moisture has increased, and negative if the soil moisture has decreased. Once ΔST is obtained, onset date, cessation and consequent LGP is estimated from monthly data. To better resolve the time scale, the ΔST is interpolated to daily data using INSTAT v3.36 with 10-day running mean, in which the daily onset date and cessation date and LGP are estimated. Finally, a minimum temperature threshold is applied which may induces early cessation of LGP. Flow chart how the research steps interlink is illustrated in Supplementary Information (SI), Figure S1 and summary for the methods how the research is performed is presented in Table S1.

3. Result and Discussion

3.1. Temperature trend analysis

The average tasmax and tasmin temperature using the model projection CCSM4 for the past were 26.5oC and 15.6oC and for the future 27.8oC and 16.8oC respectively. The future projection (2041-2070) average tasmax shows an increase of +1.3oC and tasmin of +1.2oC compared with past (1981-2010). The temperature trend test both for tasmax and tasmin and for all time periods (past, future and forward projection) revealed statistically significant and increasing trend as described below:

The tasmax increasing trend (Figure 3b) anticipates tasmax rises of about +0.023oC/yr, consistent with Jury (2015) and Knutson et al. (2013) using the rcp6 scenario (+0.025oC/yr). A similar result has been reported by IPCC assessments of tasmax over Ethiopian/NW-Ethiopian highlands by FDRE (2011); NMSA (2007). The projection of EPCC (2015) average annual temperature using RCP4.5 at the end of this century is +2.0oC, almost the medium of the projection (+2.8oC) difference obtained from the RCP6 scenario used by this study. Note that RCP4.5 (650ppm CO2 eq) and RCP6 (850ppmCO2 eq) are stabilization scenarios without an overshot pathway after 2100.

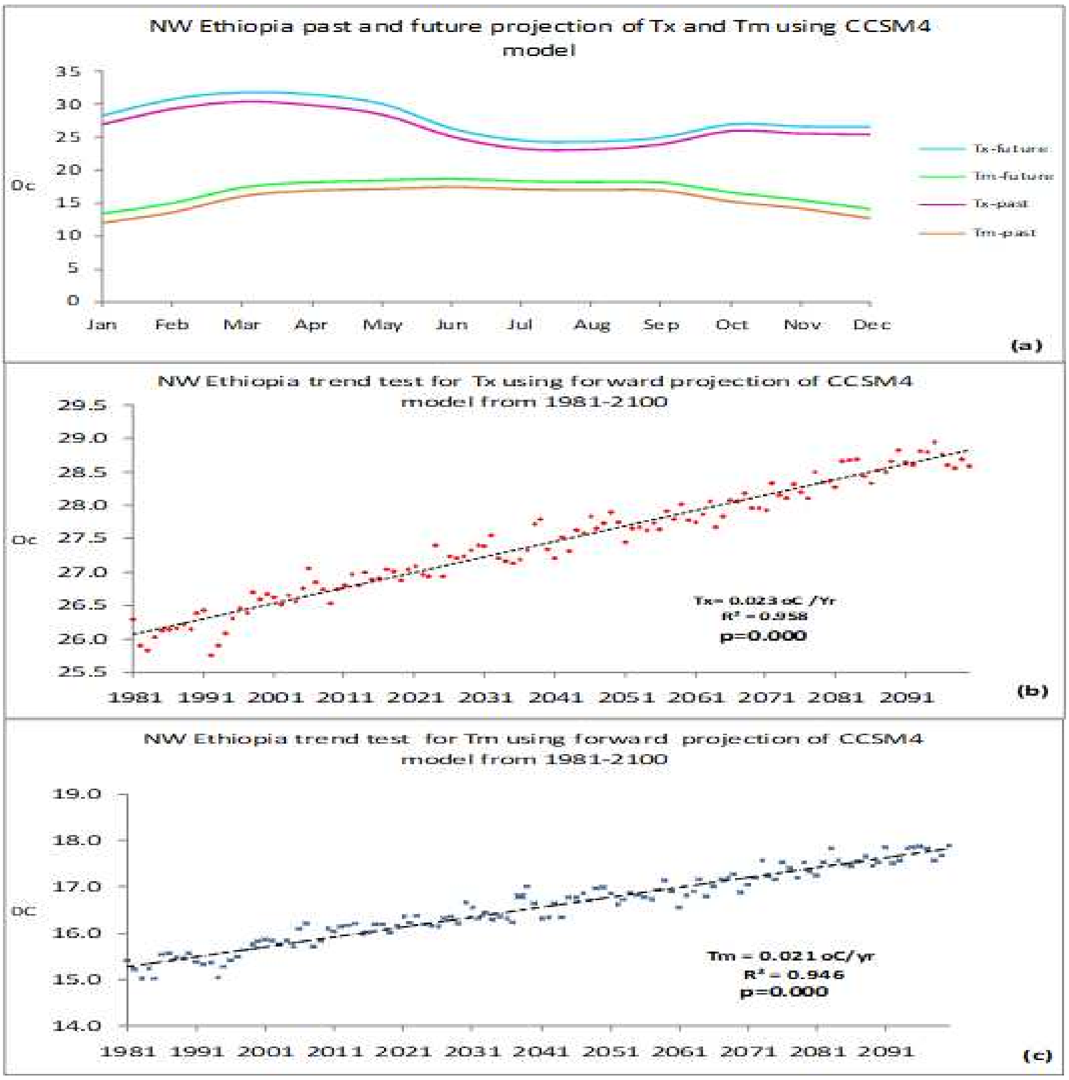

Figure 3. (a) Annual cycle comparison of CCSM4 projection of past (1981-010) and the future (2041-2070) and Regression trend test of CCSM4 forward projection (b) for tasmax and (c) for tasmin from 1981-2100.

The trend analysis of tasmin (Figure 3c) and intra-seasonal trend analysis of the hot season (February to May) and the cool season (November to January) shows significant change with rise of temperature (+0.0271oC/yr) and (+0.0226oC/yr) respectively. These show the hot season will get hot faster while the cold season gets hot slow and tasmin gets slower.

The annual cycle comparison of the past and the future tasmax and tasmin shows (R2=0.99) with higher temperature change in the future in all the months (≈+1.3oC). Regarding the hot and cool seasons: the hot season in the past was February-May and being consistent in the future with average rise of temperature from 29.6oC to 31.1oC or raising by +1.5oC and the cool season also consistent from November to January both in the past and in the future being warmer on average from 13oC to 14.3oCor raising by +1.3oC in the future (cf: Figure 3a below).

The evaluation of the spatial trend maps calculated for time period 1981-2100 using the model projectionCCSM4 indicates warming fast in the NW-Ethiopian highlands with faster warming in the central highlands (>+0.026oC/yr) which gets slower (+0.020 to +0.025oC/yr) as one move far to the edges of the highlands, Figure 4a.

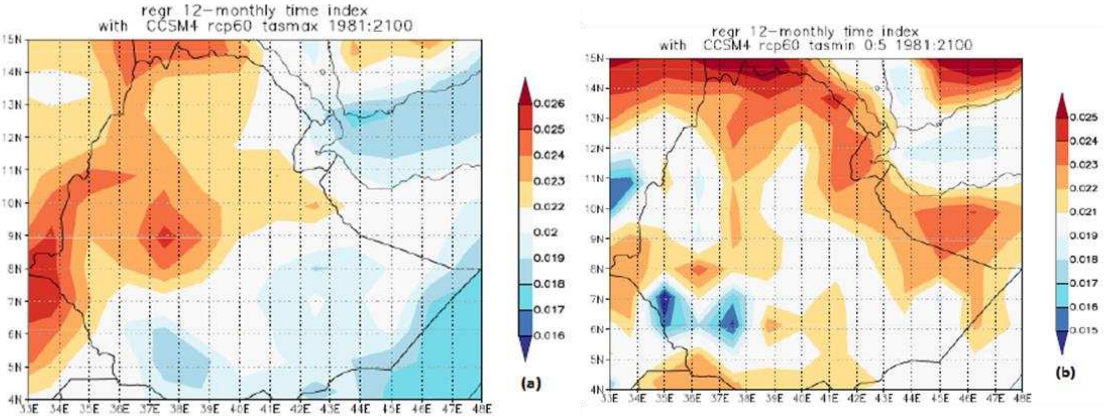

Figure 4. Spatial trend projection of CCSM4 for (a) tasmax and (b) tasmin from 1981-2100.

Tasmin shows slow warming in the western part (<+0.021oC/yr) while in the remaining part of the study area there is modest warming (+0.021 to 0.024oC/yr) and the fastest warming is projected to occur in the northern extreme part (+0.024 to +0.025oC/yr), Figure 4b. These trends agree with NMA (2007) and Alebachew and Woldeamlak (2011) and may not be entirely harmful in the region (Jury 2015). Nevertheless, projections from Conway et al. (2007) of mean annual temperature increase by the 2050s may result in teff, barley and sorghum yields declining by 8-17% and wheat and maize increasing 1-3%.

The spatial distribution of tasmax (Figure 5a below) depicted the majority of the NW-Ethiopian highlands tasmax was ranging between 23 to 26oC with hottest part from 28 to 31oC along the western border and to the extreme north of the region, whereas the coolest (< 22oC) part was the south-central part of the study area. The spatial temperature change shows increase of tasmax in the future by (>+1.3oC) but the south-central part of the highlands will most likely increase faster by +1.45oC. cf: Figure 5b.

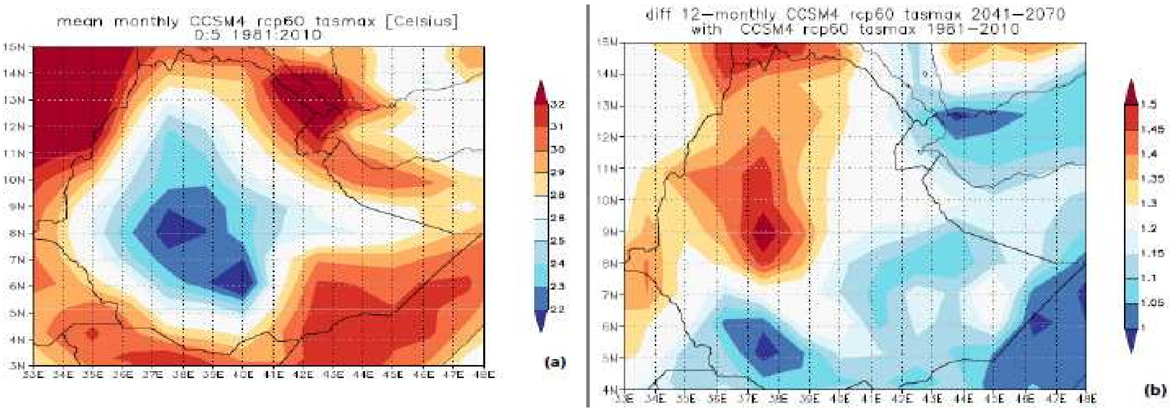

Figure 5. Average maximum temperature (Tasmax): (a) spatial distribution of the past and (b) spatial change in the future.

The spatial pattern of mean surface air minimum temperature (tasmin) simulated by CCSM4 over Ethiopia clearly identifies the cool highlands (< 15oC) surrounded by warmer lowlands (< 19oC). There are also areas in the southern central part which were the coolest (9 to 11oC) (Figure 6a). The change between past and future CCSM4 minimum air temperatures over the NW-Ethiopia highlands indicates warming (+1.13 to +1.37oC) except for the central western part which warms slowly (+0.97 to +1.13oC) while the northern extreme part warms faster (> +1.45oC) (Figure 6b). The coolest zone (9 to 11oC) in the past is anticipated to get warm by +1.2 to 1.4oC which implies the minimum temperature of this coolest zone will be ranging between (10.2 to12.4oC) in the future. The rising tasmin may improve the physiological development of crops especially at the end of the growing season.

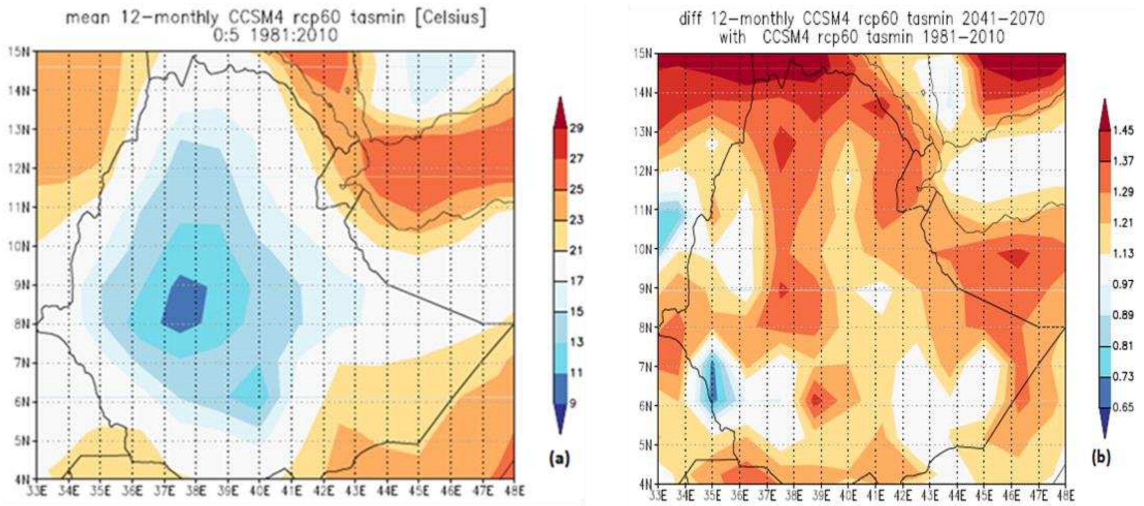

Figure 6. Average minimum temperature (tasmin): (a) spatial distribution of the past and (b) spatial change in the future.

There is high confidence in future warming so there is a need for more information on the impacts of higher temperatures on evaporation (and soil water availability), agriculture, health, and vector-borne disease (Sombroek and Gommes, 1996; Rosenzweig and Tubiello, 1997 and Conway et al., 2007). The increase in temperature due to climate change has positive impacts on crop production at high elevations in the tropics, by extending the length of the growing season; allowing earlier planting of crops and later maturation and harvesting, even to provide the opportunity for double cropping in a single season.

3.2. Rainfall change

The results from the HadGEM2-ES simulation mean average annual rainfall in the NW-Ethiopian highlands was 1210 mm (1981-2010) and 1267 mm (2041-270), an increase of +4.7% in the future, consistent with NMA (2007), Conway (2007), FDRE (2011), Conway and Schipper (2011), Jury (2013) and EPCC (2015). The slope of the annual rainfall in HadGEM2-ES forward projection (1981-2100) is upward by +0.0023 mm/day with statistically significant trend (Figure 6); consistent with Monerie et al. (as cited by Jury, 2015) and Jury (2015).

From the forward projection (1981-2100) of the seasons, the major rainfall season (JJAS) with +0.0023 mm/day and the dry season (ONDJ) with +0.0006 mm/day revealed a significant increasing trend while the short rainfall season (FMAM) showed increasing +0.00031 mm/day but not statistically significant. Given the expectation of wetter conditions, the livelihood of NW- Ethiopian farmers may be benefited from the increased rainfall assists to improve crop productions (Figure 7 left below).

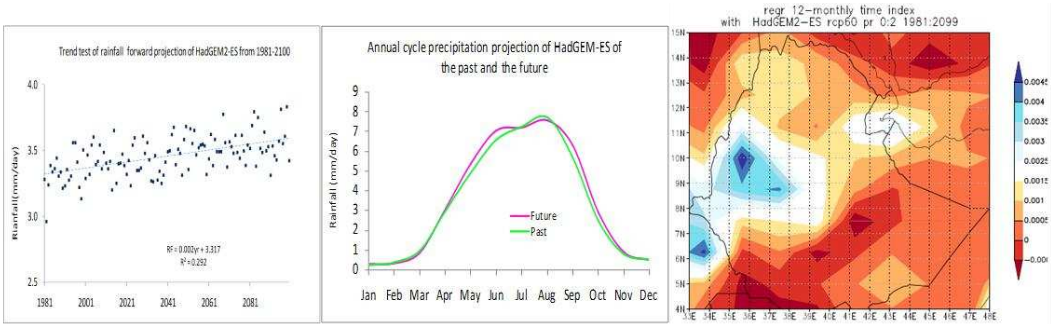

Figure 7. (Left) Regression trend of rainfall forward projection from 1981-2100 (middle) Annual cycle precipitation monthly relative (%) curve form CCSM4 projection of past (1981-2010) and future (2041-

2070) (right) Spatial trend of annual mean rainfall using Hadgem2-ES forward projection from 1981-2100.

The rainfall annual cycle of the past (1981-2010) and future (2041-2070) shows uni-modal nature consistent with result reported by NMSA (1996); Yilma and Ulrich (2004); Wing et al. (2008). The main change to the future is a seasonal broadening with more future rain in May-June and Sept-Oct (Figure 7, middle below). The season's contribution to the annual rainfall during the forward projection (1981-2100) where JJAS (67.1%), FMAM (22.6%) and ONDJ (10.3%) shows JJAS will be the major rainfall season and FMAM next and ONDJ the dry season of the study area. Here commonly the JJAS and FMAM seasons are merged seasons between May and June months.

The rainfall spatial trend analysis forward projection shows increasing trend (>+0.0005 mm/day) except for the small area around the eastern Blue-Nile basin which increases by +0.0005 to +0.0010 mm/day. The western (majority part of NW-Ethiopian highlands) showed fast increasing trend (>+0.0025 mm/day). This agrees with the time series analysis of the forward projection which depicted an increasing trend of rainfall by +0.0023 mm/day above (Figure 7, right below). From figure 8 left below: spatial distribution of the past depicts starting from the south-central part (5.25 mm/day) of the region showed a decreasing pattern driest in the northern extreme (1.75 to 2.25 mm/day) and modest along the western and eastern boundaries (2.25 to 3.25 mm/day) of the study area. However, the majority area of the region has received enough rainfall between (3.25 to 4.75 mm/day) and the Shewa highlands (8°N-9°N and 37°E - 38°E) around Wolkitie with 2000-to-3500-meter elevation was the wettest part (> 5.25 mm/day). Mean annual rainfall spatial (middle) of the past and change in the future (all units in mm/day)/right.

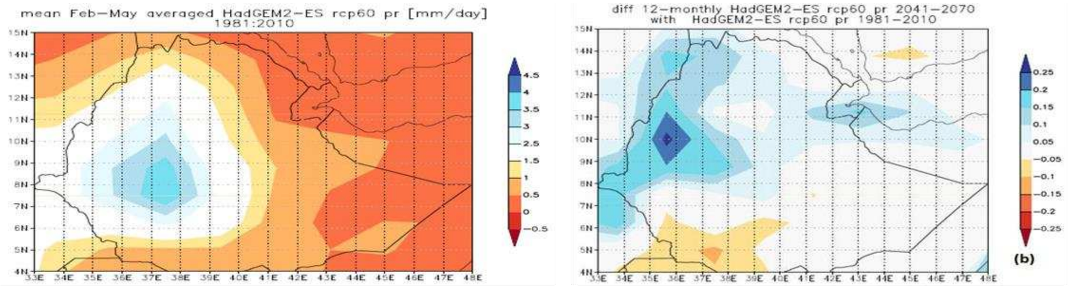

Figure 8. Spatial trend of annual mean rainfall using Hadgem2-ES for the past (left) and comparison of the difference between the past and the future (right).

Figure 8 (right) above shows the spatial distribution of annual rainfall change between the past (1981-2010) and the future (2041-2070). The result shows wetter conditions (> +0.05 mm/day) as a whole in the study area except the Wollo highlands (east-central part) with no change. The greatest increase to wetter condition (> +0.2 mm/day) is expected in the west-southern part (including the Wollega and Benshagul highlands in the western Blue-Nile basin) of the region. In addition, in the south and west-south part of the highland's regions are projected to receive a rainfall amount between 4.5 to 5.6 mm/day indicating the area will continue to have the highest rainfall potential as confirmed by NMSA (1996); Yilma and Ulrich (2004); Segele and Lamb (2005) and Gizaw (2012). Thus, one can observe that both the time series and spatial analysis of annual rainfall reveal an increase of rainfall in the NW-Ethiopian highlands in agreement with McSweeney et al. (2008).

3.3. Potential evapotranspiration

PET is helpful in determining the moisture deficit and the periods when the need for irrigation and water harvesting is high. The PET is evaluated from the surrogate sensible heat flux (shf) derived from the CMIP5 rcp6 HadGEM2-ES model shf output after adjustment adjshf (+2 mm/day). Annual cycle of PET of the past and the future shows mean 3.64 mm/day and minimum 3.62 mm/day and maximum 3.81 mm/day and mean 3.55 mm/day, minimum 3.51 mm/day and maximum 3.70 mm/day

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respectively. This agrees with Allen et al.'s (1998) suggestion of average PET between 3mm/day to 5 mm/day for humid and sub-humid regions with a mean daily temperature around 20^{O}C.

The annual cycle pattern of PET depicts an annual cycle with little change from June-October, then increases to the maximum during the hot season (February to April) (figure3.7 left). PET is consistent with temperature, as reported by Fazzini et al. (2015) in their study of the climate of Ethiopia. To compare the change in PET from past to future, a trend test was performed. The result revealed the 1981-2070 trend decreasing by (-0.0003 mm/day) and the 2041-2070 trend increasing by (+0.0012 mm/day) but the changes for both are not significant with p value p>0.1517. However, the PET shows a significant trend change decrease by (-0.0036 mm/day) in the past (1981-2010). From here onwards in this chapter all the spatial maps are in shf (W/m²/month) but to keep consistency the presentation is outlined by changing shf in W/m² to PET/shf in mm. Thus, the forward projection (1981-2070) regression trend spatial map for PET/shf shows very little change (-0.0010 to +0.0010 mm/day) in the majority area and a decreasing trend (-0.0010 to - 0.0031 mm/day) in the north-western extreme (Figure 9 right). In general, the forward projection of the spatial trend is in agreement with the time series trend.

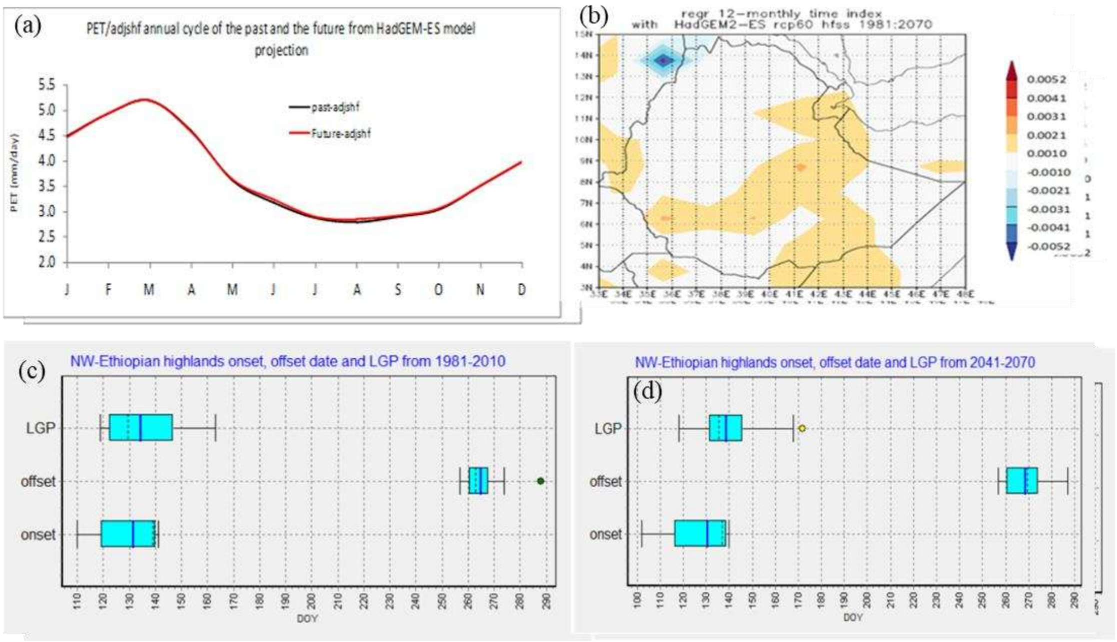

Figure 9. Spatial trend of annual mean rainfall using Hadgem2-ES for the past (a), comparison of the difference between the past and the future (b), box and whisker plot of NW-Ethiopian highlands onset and cessation date and LGP of the past (c) and the future (d) (dash bar-median, boxes 25th-75th percentile; whiskers 10th/90th percentile) (* - extreme values).

3.4. Soil water balance.

The water balance technique according to Subrahmanyam, (1980) is a quantitative estimation of water that circulates in between the hydrosphere, lithosphere, and the atmosphere. The soil water balance method used to compute soil water balance by extracting precipitation (P) and PET (Es) data from the HadGEM2-ES CMIP5 rcp6 model both for the past (1981-2070) and the future. Before proceeding to the evaluation of the water balance (P-Es) of the past and the future, trend analysis is performed to check whether the change is statistically significant. The forward projection (1981-2070) and the past revealed a significantly increasing trend of (+0.035 mm/day) and (+0.139 mm/day) whereas the trend test for the future shows a decreasing trend (-0.017 mm/day) but the change is not significant.

The computational procedures used to estimate soil water content change ($\Delta ST > 0$) most likely gives reliable results regarding soil water content and its implication in the study area. In line to this

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the result showed excess forcing (ΔST > 0) during the months June to September (4 months); while deficit forcing (ΔST ≤ 0) months from October to May (8 m0nths) both in the past and in the future (For the computation result table 3.1 below).

3.5 Length of growing season

The annual cycle soil water change (ΔST) of each year was computed both for the past and the future. In the NW-Ethiopian highlands estimates of the average reserve of soil water storage was 82 mm/month in the past and 84 mm/month projection in the future. Both are affected positively by (ΔST > 0) starting from onset day of the year (DOY). However, the soil water content changes from the first day (offset DOY) (ΔST< 0) influences the driving soil water content to become deficient.

The trend analysis test revealed an decreasing trend of onset date (-0.021 day/yr), cessation date (-0.300 day/yr) in the past but LGP with increasing trend (+0.033 day/yr) and in the future decreasing trend of cessation date (-0.039 day/yr) and LGP (-0.335day/yr) while onset date depicted increasing trend (+0.295 day/yr); however, the change are not statistically significant for all the parameters at 0.05 significant level. The statistical median result of onset date was 139 DOY, cessation date 263 DOY and LGP 130 days in the past and in the future the onset date, cessation date and LGP are likely to be 137 DOY and cessation date 270 DOY implies 136 LGP days.

Almost slightly similar result of LGP ranging between 137 to 205 days for the NW-Ethiopian highlands has been reported in the mapping of climate vulnerability and poverty in Africa (current condition of 2000) by ILRI (2006). Allen et al. (1998) has also suggested a plant date on April and LGP 180 days for maize (grain) for east Africa high altitude areas.

The LGP estimation obtained in both time periods has minimum LGP ≥118 days which are above the threshold LGP (90 days). According to Masresha (2003), most crops grown in Ethiopia with the exception of some pulses and very low yielding varieties of Teff (common cereal food in Ethiopia) and wheat require a growing period of at least 90 days. In addition, Belay (2001) has also recommended 90 days LGP as optimum LGP in the case of Ethiopia.

Figure 9b box the evaluation of variability of length of growing seasons depicted the onset dates were highly variable, next the LGP and the offset dates less variable in the past, but in the future offset dates is likely to be highly variable and the LGP and onset dates less variable. In general, the evaluation of onset date, end date and LGP of crop growing seasons under climate change scenario showed the importance of early planting at the month of May and harvesting at end of September with LGP suitable for single and to some extent double cropping both in the past and future with a slightly longer growing season in the future which most likely benefit the agriculture production over NW-Ethiopian highlands.

4. Conclusions and Summary

The study has presented detailed analyses of climate change and its impact on soil water balance and length of growing seasons in the NW-Ethiopian highlands. Data sets from station observations and gridded observation, reanalysis and simulations of CMIP5 rcp6 models were employed for this purpose. A number of analysis tools such as trends, spatial maps as well as various measures of bias and dispersion for comparison of datasets and different methods were utilise for analysis of results. The stepwise criteria used for the validation of the models revealed CCSM4 (for tasmax) and HadGEM2-ES (for precipitation and PET/adjshf) were the models achieved most of the criteria and used as a data source for the analysis and interpretations of climate change, climate variability and extremes and estimate soil water balance and length of growing seasons of the past and the future.

Temperature has a significantly increasing trend in all time periods; however, the tasmax increases faster than tasmin and the hot season increases faster than the cold season in the past and the same increasing change in the future. In agreement to the time series, the spatial distribution map of tasmax and tasmin projection indicates the region will likely get hot faster. The rainfall trend analysis is mixed in the NW-Ethiopian highlands. In which the trend of JJAS season in all time periods have significant increasing change while the remaining seasons and annual rainfall are non-significant (no trends). The spatial distribution of the annual and the seasons rainfall agrees with the time series trend test in which the NW-Ethiopian highlands expected to become wetter, especially in the south-western part.

The extreme change of minimum rainfall change is beyond normal that requires substantial adjustments in agricultural and water management to adapt effectively; nevertheless, the maximum rainfall change is likely to benefit agriculture except offset sometimes in flood-prone areas. On the other hand, extremes return period taking other factors at optimum shows the region had received and is likely to receive enough annual and JJAS seasonal rainfall for rain-fed agricultural practice. The FMAM season extreme probabilities show the season could not be operational for rain-fed crop production separately, but the season can be utilized for early planting from April to May months so that the region is likely to benefit from the additional length of the growing season. As ONDJ season is anticipated to come with substantial amount of rainfall; the season can be considered as another option of a growing season for short cycle crops that likely needs additional water supply or used to extend the JJAS season; otherwise, early warring should be considered as it has the potential to disrupt crop production during the harvesting time.

The NW-Ethiopian highlands have experienced frequent extreme and severe droughts in the past; however, drought in future is likely to be more than 80% normal (non-drought) years.

The trend of PET is mixed in which the change is statistically significant in the past only. The general comparison result from the temporal and spatial distribution of the annual and seasonal rainfall and temperature with PET revealed low temperature characterise low PET rate and high temperature characterise high PET rate. But in the case of rainfall, low rainfall characterise high PET rate and high rainfall characterise low PET rate. The water balance technique obtained by applying quantitative estimation of soil water balance for both time periods revealed significantly increasing trend for the past but a decreasing trend (not statistically significant) in the future. The average annual total water balance conditions both in the past and in the future showed PET exceeds rainfall or losses exceed the gains in the study area.

The importance of early planting at the month of April/May and harvesting at end of September with LGP suitable for single cropping and to some extent double cropping both in the past and future has been obtained from the result of this study. The variability of length of growing seasons depicted the LGP dates were highly variable, next the onset dates and the offset dates less variable in the past but in the future onset dates are likely to be highly variable; while the LGPs and onset dates less variable.

Supplementary Materials: The following supporting information can be downloaded at the website of this paper posted on Preprints.org.

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